Hadley Centre for Climate Prediction and Research
The Met. Office London Road Bracknell RG12 2SY UK
© British Crown copyright 1999 99/812
ISBN 0 86180 350 7

Designed and produced by Met Office Communications

DETR
Environment
Transport
Regions

Climate change and its impacts

Stabilisation of CO_2 in the atmosphere

October 1999

The Met.Office

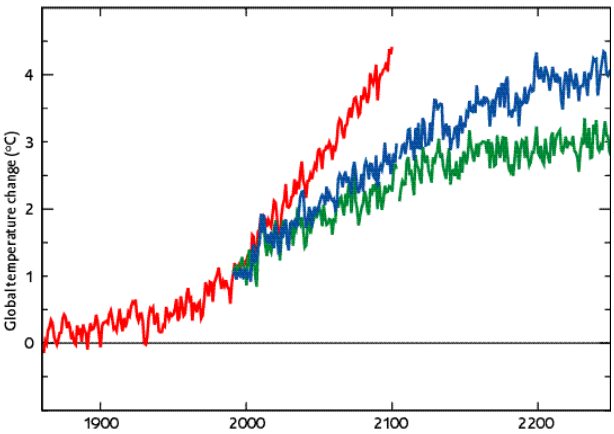
Some recent results from research sponsored by the
United Kingdom Department of the Environment, Transport and the Regions
in partnership with the Scottish Executive, the National Assembly for Wales
and the Department of the Environment for Northern Ireland.

This report can also be seen at

www.met-office.gov.uk/sec5/CR_div/CoP5/

In reports issued in 1997 and 1998, we have looked at the climate change due to a 'business as usual', or unmitigated, emissions scenario and the socio-economic impacts resulting from it. In this report, in order to contribute to the discussion on interpreting Annex 2 of the UN Framework Convention on Climate Change, we investigate two scenarios of reduced emissions, leading to a stabilisation of the concentration of CO_2 in the atmosphere, at 550 and 750 parts per million (ppm); about twice and three times pre-industrial levels respectively. In the first section the climate consequences are predicted, and these predictions are used as scenarios to make the first assessments of global impacts in five areas: natural vegetation, water resources, food supply, coastal flooding and human health. The impacts are compared in each case with those which would arise if emissions were not mitigated, concentrating on changes between the present day (defined as the period 1961–90) and 30-year periods centred on the 2020s, the 2050s and the 2080s. In addition, changes are illustrated over the longer term from the stabilisation scenarios, up to the 2230s. All models and methods used in this report have been validated and peer-reviewed.

The emissions scenarios leading to stabilisation of CO_2 will, in the next two to three centuries, lead to an effective stabilisation of climate change and socio-economic impacts (apart from sea-level rise), as intended. However, there are more important differences between the impacts of these scenarios in the short term. The work presented here illustrates that many of the changes and consequent impacts resulting from unmitigated emissions of carbon dioxide are delayed by 50–100 years if emissions scenarios leading to stabilisation of CO_2 are considered. Clear indications are given that stabilisation of CO_2 at 550 ppm not only substantially reduces the magnitude of changes and impacts over the next century, but may also prevent some of the more serious impacts in certain regions. For example, with unmitigated emissions, and even



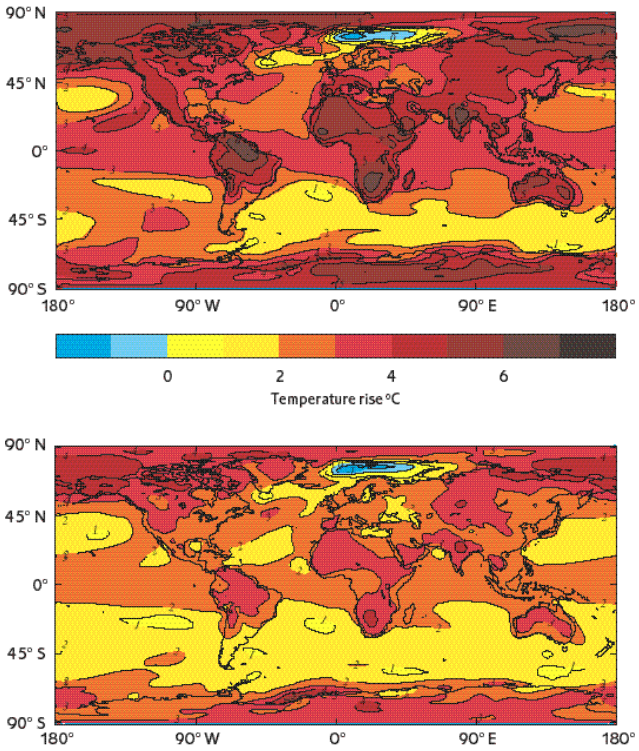
The global average temperature rise resulting from the unmitigated emissions scenario (red), an emission scenario which stabilises CO_2 concentrations at 750 ppm (blue) and at 550 ppm (green).

emissions leading to stabilisation of CO_2 at 750 ppm, significant losses of tropical rainforest in South America, and increases in water resource stress in some countries in Europe and the Middle East are predicted. These impacts may be avoided by stabilisation at 550 ppm.

The key findings of this report are as follows:

Recent climate changes

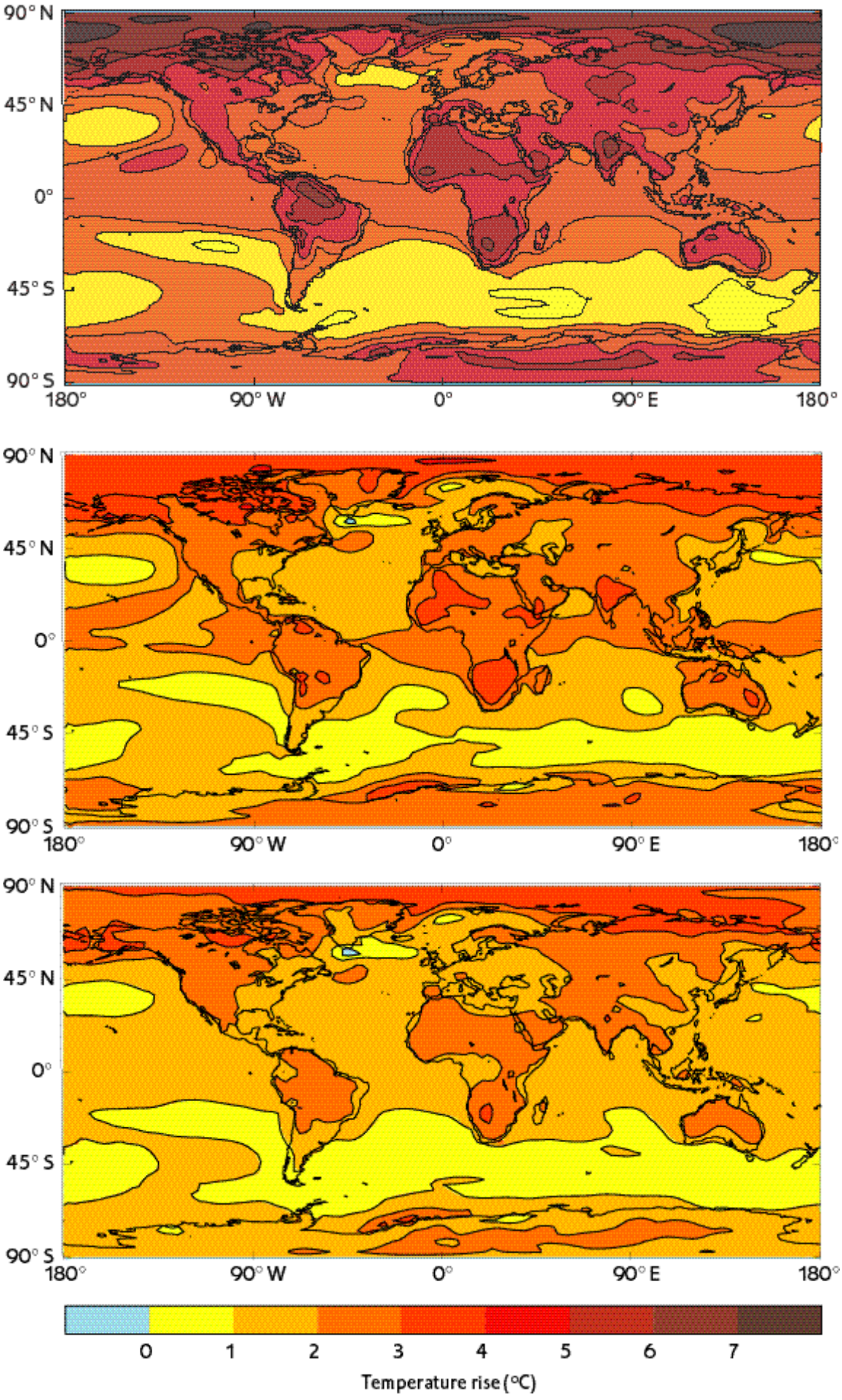
- Partly because sea-surface temperatures in the tropical Pacific have moved into a cool La Niña phase, the annual global mean surface temperature in 1999 will, as expected, be substantially cooler than the record year of 1998, although it is still likely to be one of the highest ten on record.
- New analyses of observations show that the free atmosphere (at a height of 3–5 km) has clearly warmed over the past 35 years, although not always in concert with the surface. The extent of Arctic sea ice has decreased over the last three decades, but not that in Antarctica.



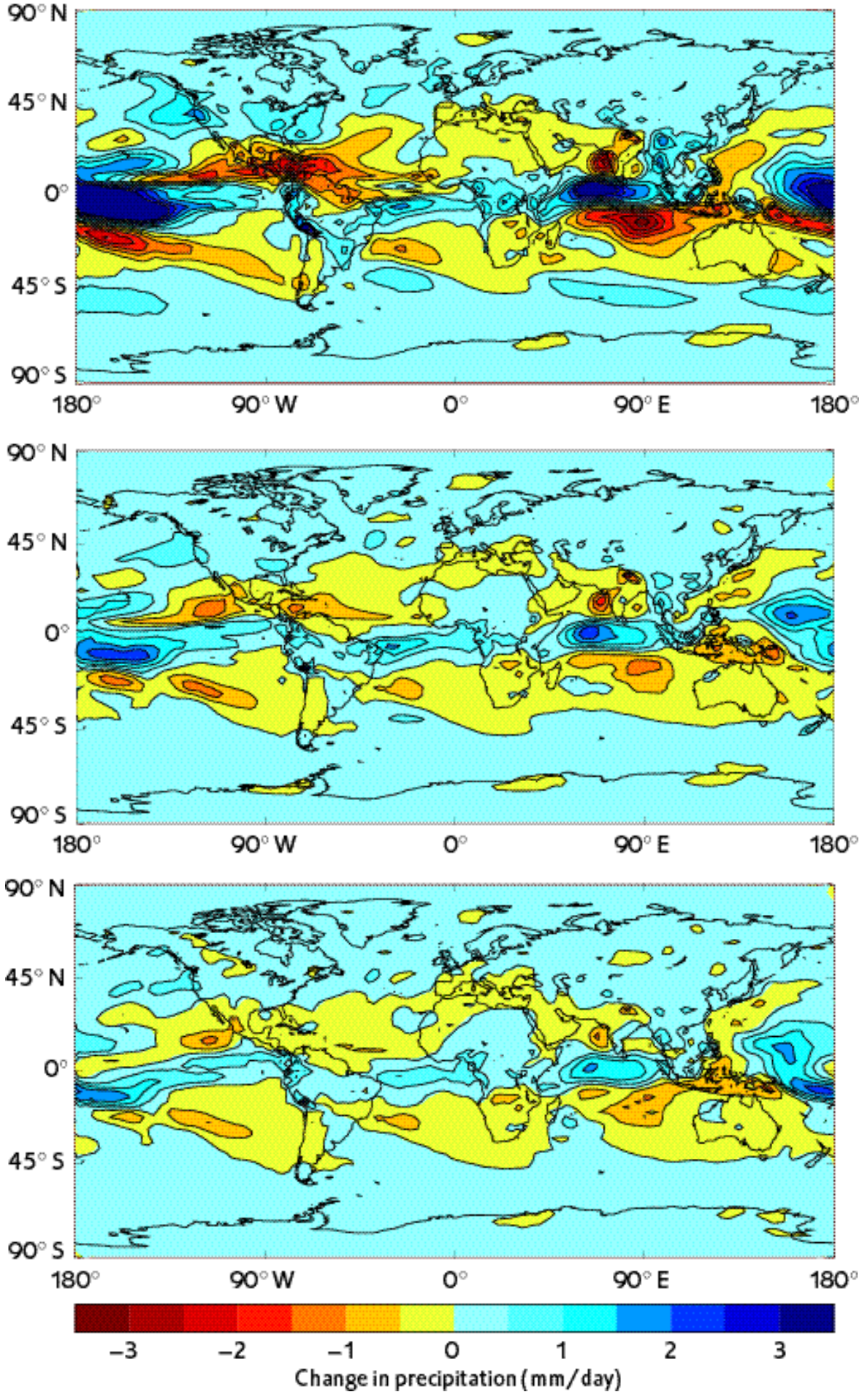
Patterns of annual average temperature rise from today to the 2230s, resulting from an emissions scenario which stabilises CO_2 at 750 ppm (top) and one which stabilises at 550 ppm (bottom).

Climate change predictions

- With unmitigated emissions, global average temperature is predicted to increase by 3 °C by the 2080s compared to the present. Land areas will warm twice as fast as oceans, winter high latitudes are also expected to warm more quickly than the global average, as are areas of northern South America, India and southern Africa. Large changes in



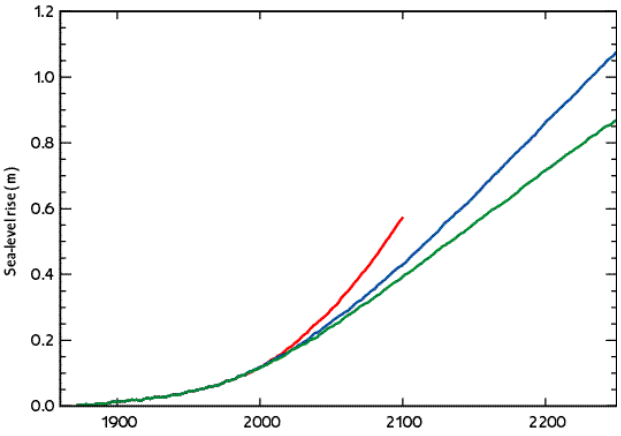
Patterns of annual average temperature rise from the present day to the 2080s, resulting from the unmitigated emissions scenario (top), an emissions scenario which stabilises CO_2 at 750 ppm (middle) and one which stabilises at 550 ppm (bottom).



Patterns of change in annual average precipitation from the present day to the 2080s, resulting from the unmitigated emissions scenario (top), an emissions scenario which stabilises CO_2 concentration at 750 ppm (middle) and one which stabilises at 550 ppm (bottom).

precipitation, both positive and negative, are seen, largely in the Tropics.

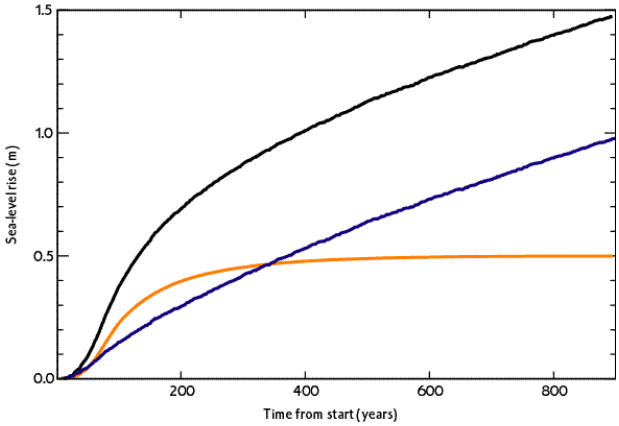
- Emissions scenarios leading to stabilisation of CO_2 in the atmosphere will reduce the rate of change of global climate. A rise of 2 °C above the present day, expected by the 2050s with unmitigated emissions, would be delayed by 50 years if CO_2 was to be stabilised at 750 ppm, and by over 100 years with stabilisation at 550 ppm. Patterns of temperature and precipitation change are broadly similar under all scenarios, with the pattern strength corresponding to global average temperature change.
- By the 2230s, global temperatures will have risen by just over 2 °C above today's under the 550 ppm stabilisation scenario, and just over 3 °C under the 750 ppm scenario.
- A rise in sea level of 40 cm expected by the 2080s would be delayed by about 25 years with stabilisation at 750 ppm and 40 years with stabilisation at 550 ppm.



The rise in sea level resulting from the unmitigated emissions scenario (red), an emissions scenario which stabilises CO_2 concentration at 750 ppm (blue) and at 550 ppm (green).

Natural ecosystems

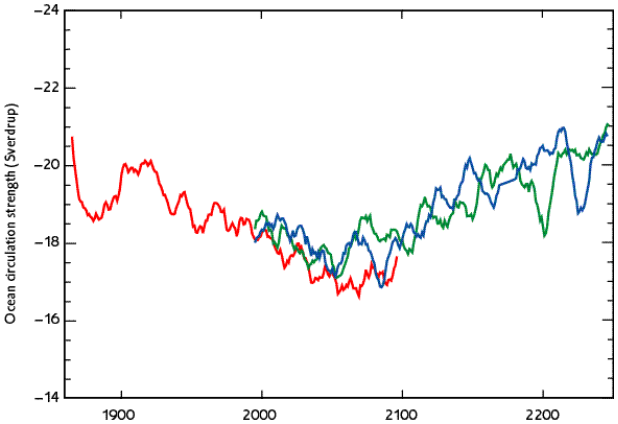
- With unmitigated emissions, substantial dieback of tropical forests and tropical grasslands is predicted to occur by the 2080s, especially in northern South America and central southern Africa. Considerable growth of forests is predicted to occur in North America, northern Asia and China.
- Under emissions scenarios leading to stabilisation of CO_2 at 750 ppm, the dieback of tropical forests is delayed by about 100 years, but under stabilisation at 550 ppm this loss is substantially reduced, even by the 2230s.
- The absorption of carbon dioxide by vegetation increases during the 21st century in all scenarios. But, due to dieback in tropical vegetation, this sink is lost in the 2070s with unmitigated emissions and about 100 years later with emissions which stabilise CO_2 concentrations. Without this sink, CO_2 concentrations will be higher than assumed in the climate model, and hence climate change will be greater than current predictions.



The long-term commitment to sea-level rise, resulting from a 1% increase in CO_2 for the first 70 years and no further change thereafter. The thermal expansion (purple) and ice-melt (orange) components are shown, together with the total (black).

Water resources

- With unmitigated emissions, by the 2080s, there are large changes predicted in the availability of water from rivers. Substantial decreases are seen in Australia, India, southern Africa, most of South America and Europe, and the Middle East. Increases are seen across North America, Asia (particularly central Asia) and central eastern Africa.
- An emissions scenario leading to stabilisation of CO_2 at 750 ppm generally slows down the rate of change in river flows, compared to an unmitigated emissions scenario, by about 100 years (more in Asia, slightly less in Europe). Stabilisation at 550 ppm delays the change still further, particularly in South America and Asia.
- Water resource stress due to climate change by the 2080s is predicted to worsen in many countries, for example, in northern Africa, the Middle East and the Indian subcontinent, but will improve elsewhere, for example, in China and the USA. Overall, about three billion people will suffer

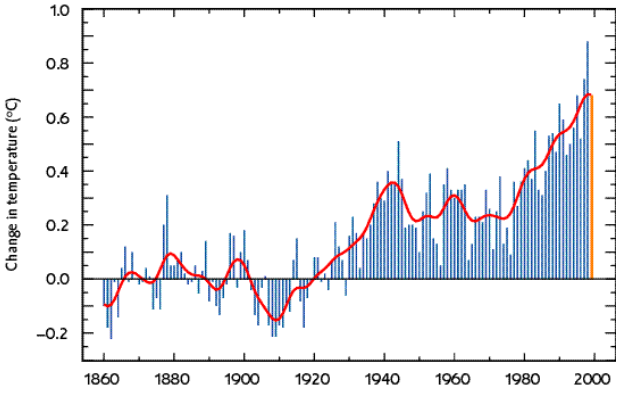


Changes in strength of the North Atlantic Ocean circulation resulting from the unmitigated emissions scenario (red), and emissions scenarios which stabilise CO_2 at 750 ppm (blue) and 550 ppm (green).

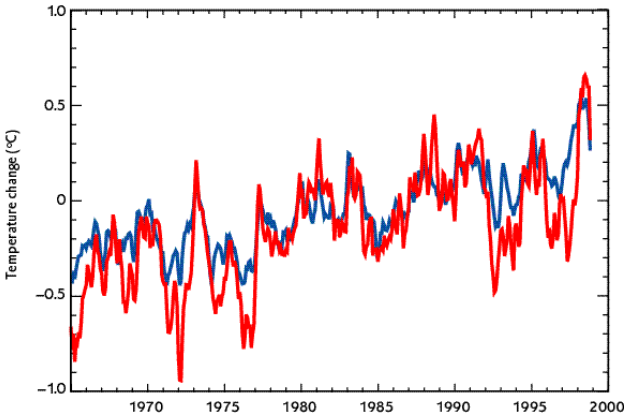
increased water stress. Emissions leading to stabilisation at 550 ppm reduce this number to about one billion. Stabilisation at 750 ppm has little effect on the total.

Agriculture

- By the 2080s, climate change and CO_2 increases due to unmitigated emissions are estimated to increase cereal yields at high and mid-latitudes, such as North America, China, Argentina and much of Europe. At the same time, cereal yields in Africa, the Middle East and, particularly, India are expected to decrease.
- With emissions leading to CO_2 stabilisation, fewer regions experience negative impacts, although even under the 550 ppm scenario Africa and India are still adversely affected, and parts of South America are worse off than under unmitigated emissions. Under the 750 ppm stabilisation scenario, increasing CO_2 and climate change benefit production in areas of central Asia.
- The food system may be expected to accommodate such regional variations at the global level, with production, prices and the risk of hunger being relatively unaffected. However, some regions, particularly Africa, will be adversely affected, experiencing marked reductions in yield, decreases in production, and increases in the risk of hunger.
- Reduction of emissions, leading to stabilisation of CO_2, appears to provide a way, in the short- to medium-term, of reducing the impacts of climate change on world food supply.



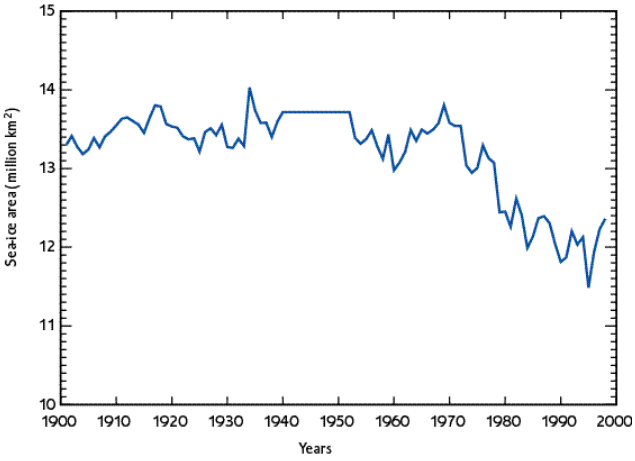
Global mean surface air temperature for each year from 1860 to 1999 (blue bars), relative to that at the end of the last century, together with a smoothed curve (red). The 1999 value (orange bar) includes observations up to the end of July.



Change in monthly average air temperature from 1965 to 1999 at the surface (blue) and in the free atmosphere at a height of 3–5 km (red).

Coastal effects

- With unmitigated emissions, sea level will be about 40 cm higher than today by the 2080s, and this is estimated to increase the annual number of people flooded from 13 million to 94 million. 60% of this increase will occur in southern Asia (along coasts from Pakistan, through India, Sri Lanka and Bangladesh to Burma), and 20% will occur in South East Asia (from Thailand to Vietnam including Indonesia and the Philippines).
- The flood impacts of sea-level rise are reduced by the emissions scenarios leading to stabilisation of CO_2; by the 2080s, the annual number of people flooded is estimated to be 34 million under the 750 ppm scenario and 19 million



The observed change in Arctic sea-ice area, 1900 to 1998. The average extent for the period 1939–1952 is shown as the data are not sufficient to show year-to-year variations.

The impacts of climate change on natural vegetation

under the 550 ppm scenario. Again, most of those flooded will be in southern and South East Asia.

- Under all emissions scenarios, sea-level rise will compound the existing decline of coastal wetlands due to direct human destruction. Under the stabilisation scenarios, wetlands will have longer to adjust and this will significantly reduce losses and aid their long-term survival.
- The continued rise in sea level even under the stabilisation scenarios would produce a range of progressive impacts on coastal lowlands and on low-lying coastal islands.

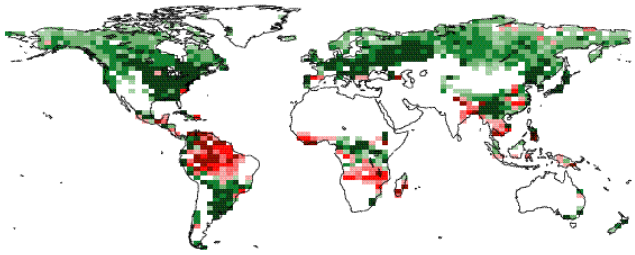
Human health

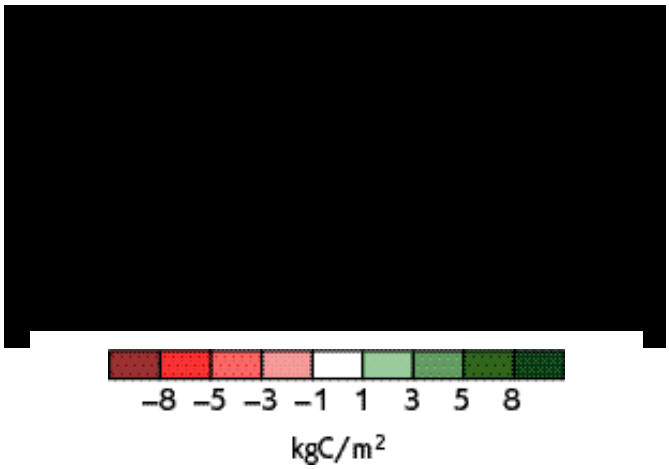
- In the 2080s, an estimated 290 million additional people worldwide will be at risk of *falciparum* malaria (clinically more dangerous than the more widespread *vivax* malaria) due to climate change from unmitigated emissions. The greatest increases in risk are projected for China and central Asia.
- Under emissions scenarios which stabilise CO_2 at 750 ppm and 550 ppm, lesser numbers of people will be at risk of malaria, estimated to be within the range 175 to 255 million. These are indicative estimates of the potential benefits of stabilisation. The geographical areas of additional risk are broadly similar to those for the unmitigated scenarios.
- Human-induced warming will reduce the risk of mortality in many large temperate-zone cities, as the estimated reduction in winter-related mortality exceeds the increase in heat-related summer mortality. This benefit is not as great under emissions scenarios leading to CO_2 stabilisation. Of the five cities studied, only one shows an overall increase in annual mortality, which is moderated under the stabilisation scenarios.

Contributors: John Mitchell, Chris Coghlan, Tim Johns, Nick Rayner, Jonathan Gregory, Jason Lowe, David Parker, Margaret Gordon and Geoff Jenkins at the Hadley Centre, The Met. Office; Mike Hulme, David Viner and Phil Jones at the Climatic Research Unit, University of East Anglia.

Summary

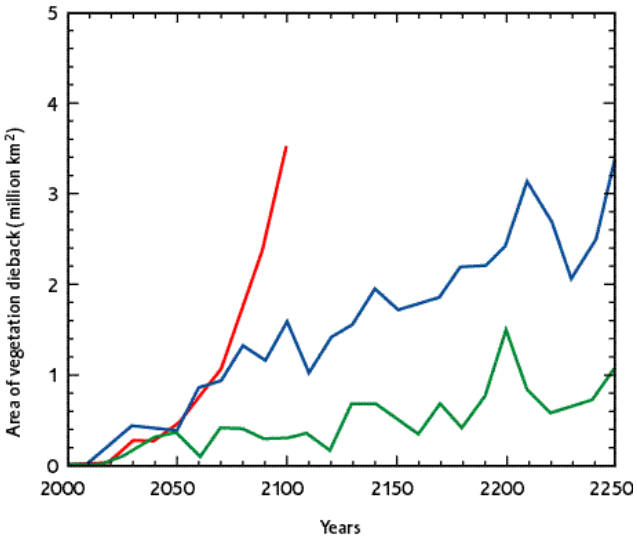
- Partly because sea-surface temperatures in the tropical Pacific have moved into a cool La Niña phase, the annual global mean surface temperature in 1999 will, as expected, be substantially cooler than the record year of 1998, although it is still likely to be one of the highest ten on record.
- New analyses of observations show that the free atmosphere (at a height of 3–5 km) has clearly warmed over the past 35 years, although not always in concert with the surface. The extent of Arctic sea ice has decreased over the last three decades.
- With unmitigated emissions, global average temperature is predicted to increase by 3 °C by the 2080s compared to the present (taken as 1961–90). Land areas will warm twice as fast as oceans, winter high latitudes are also expected to warm more quickly than the global average, as are areas of northern South America, India and southern Africa. Large changes in precipitation, both positive and negative, are seen, largely in the Tropics.





Change in global vegetation biomass between the present day and the 2230s for the two stabilisation scenarios; 750 ppm (top) and 550 ppm (bottom).

- Emissions scenarios leading to stabilisation of CO_2 in the atmosphere will reduce the rate of change of global climate. A rise of 2 °C above the present day, expected by the 2050s with unmitigated emissions, would be delayed by 50 years if CO_2 was to be stabilised at 750 ppm, and by over 100 years with stabilisation at 550 ppm. Patterns of temperature and precipitation change are similar under all scenarios, with the pattern strength corresponding to global average temperature change.
- By the 2230s, global temperatures will have risen by just over 2 °C above today's under the 550 ppm stabilisation scenario, and just over 3 °C under the 750 ppm scenario.



The area of vegetation dieback in response to climate change with unmitigated emissions (red), stabilisation at 750 ppm CO_2 (blue line) and stabilisation at 550 ppm CO_2 (green line). Here vegetaton dieback is defined as a reduction in biomass to less than 10% of the 1990s level. Note the amount of vegetation dieback is significantly reduced with 550 ppm stabilisation.

- A rise in sea level of 40 cm, expected by the 2080s, would be delayed by about 25 years under emissions leading to stabilisation at 750 ppm and 40 years with stabilisation at 550 ppm.

Introduction

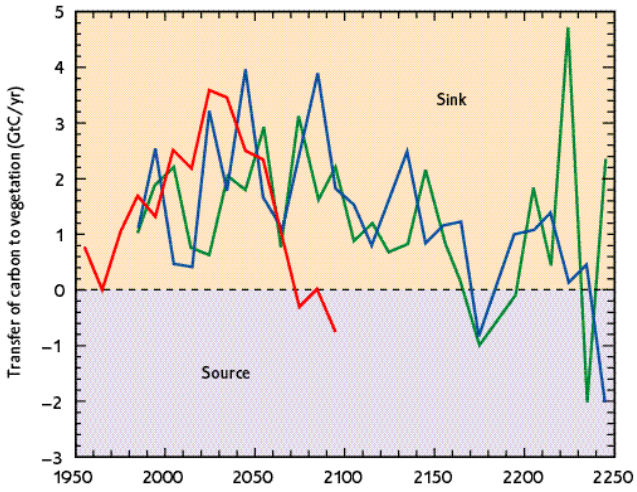
Previous reports have shown the climate change and socio-economic impacts resulting from the 1995 IPCC 'business as usual', or unmitigated, emissions scenario. In 1997, IPCC suggested two scenarios of emissions reductions which stabilised CO_2 concentrations at 750 ppm and 550 ppm, about twice present-day and pre-industrial levels respectively. The profiles of anthropogenic emissions and the resulting CO_2 concentration profiles are shown below; it can be seen that emissions for either of the concentration stabilisation pathways are very much lower than the 'business as usual' case. IPCC made no assessment of the way in which these emissions were to be reduced.

This report explores the climate and socio-economic impact of these two mitigation scenarios, compared to those which are predicted to arise from a 'business as usual' or unmitigated emissions scenario. The socio-economic impacts assume a common future for global population, starting at 5.3 billion in 1990 and rising to 8.1 billion in the 2020s, 9.8 billion in the 2050s and finally 10.7 billion in the 2080s. Similarly, GDP/capita is assumed to rise from the current $3,800 to $6,800 in the 2020s, $10,700 in the 2050s and $17,700 in the 2080s (1990 US dollars). Beyond the 2080s, only estimates of the effects of climate change are presented, rather than the socio-economic impacts, as the latter would require projections of GDP and population beyond 2100 in which there is very little confidence.

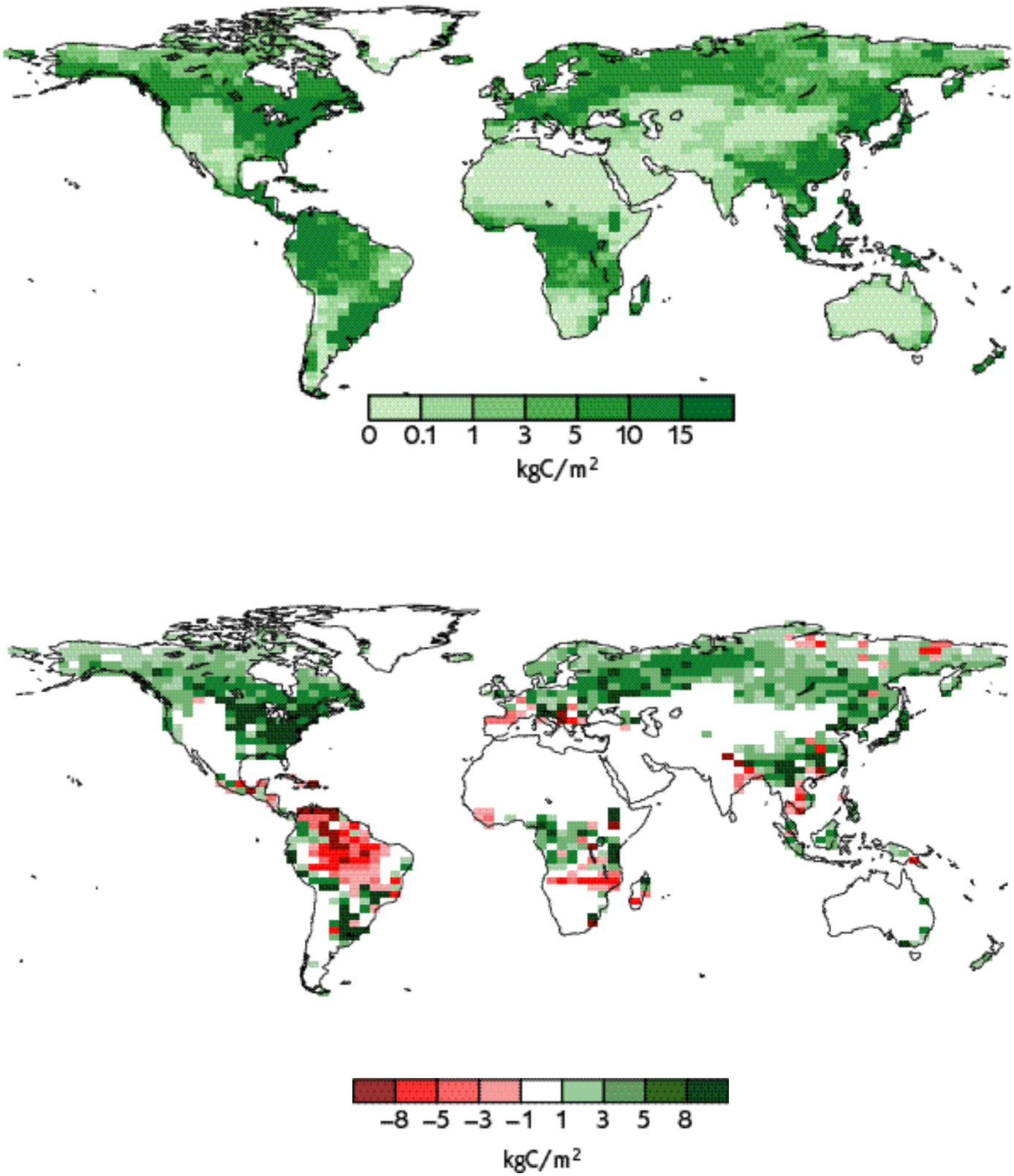
The model used to generate climate scenarios for this study was the second Hadley Centre climate model, which has a climate sensitivity close to the IPCC 'best estimate' value. The changes arising from a 'business as usual' emissions scenario (close to IPCC IS92a), in which CO_2 and other greenhouse gases increase without mitigation have been described in an earlier report (December 1997); these are used for comparison in this report, referred to as the 'unmitigated emissions scenario'. For the current report, the model was driven with CO_2 emissions scenarios which stabilise its concentration, but did not include increases in other greenhouse gases or aerosols. Experiments were started from 1860, to allow the full effect of pre-1990 emissions to be taken into account, and run to 2250 as stabilisation of CO_2 at 750 ppm is not achieved until about 2225 in the IPCC scenarios.

Climate change under stabilisation scenarios

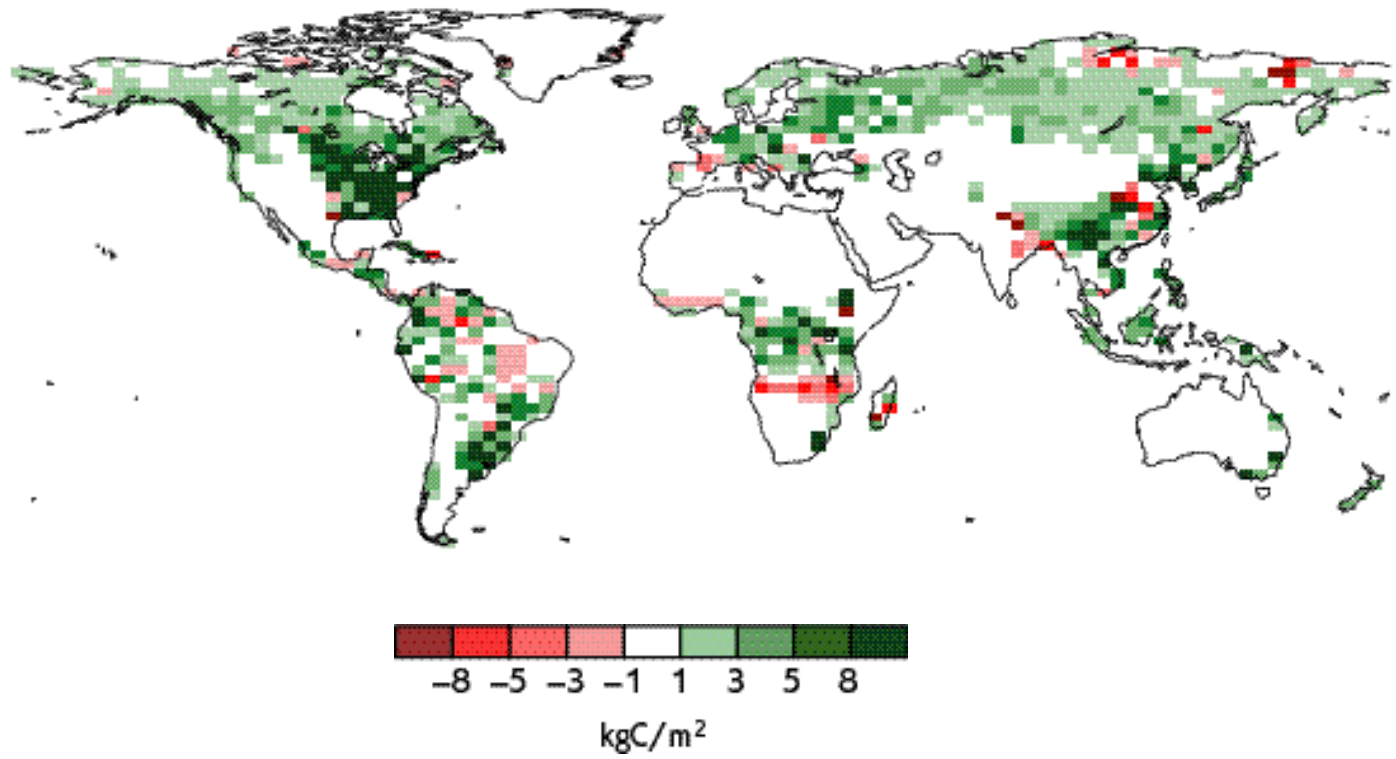
The changes in global average surface temperature for the stabilisation scenarios compared to the unmitigated scenario are shown below. With unmitigated emissions, temperatures

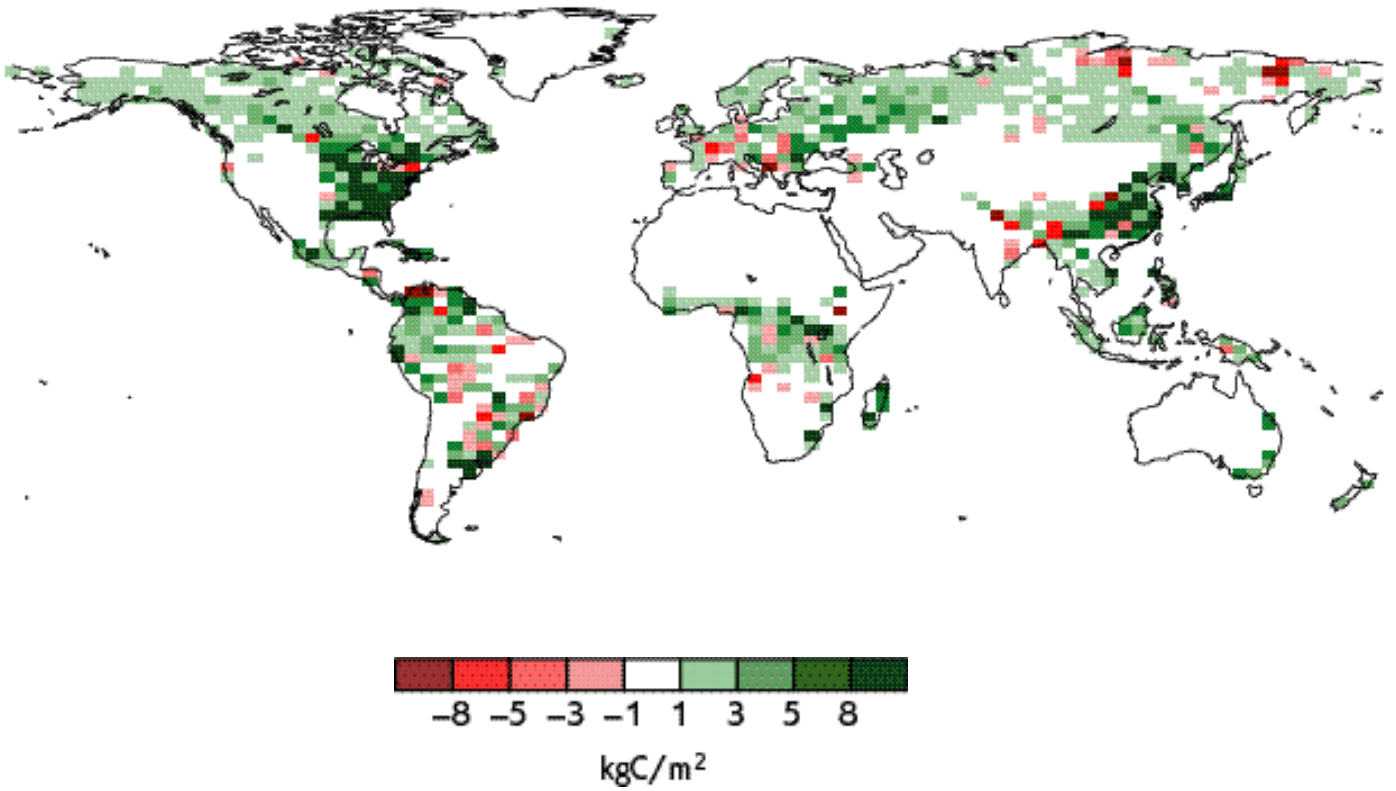


The net uptake of carbon to the land surface (i.e. the rate of increase in the terrestrial carbon store) in response to climate change with unmitigated emissions (red line), stabilisation at 750 ppm CO_2 (blue line) and stabilisation at 550 ppm CO_2 (green line). Note the loss of carbon sink occurs in the 2070s with unmitigated emissions, but is delayed around 100 years with 550 ppm and 750 ppm stabilisation.



Global vegetation biomass in the 1990s (top) and the change in biomass between the 1990s and the 2080s in response to climate change due to unmitigated emissions (bottom).





The change in biomass between the 1990s and the 2080s in response to climate change due to emissions which stabilise CO_2 at 750 ppm (top) and 550 ppm (bottom).

The impacts of climate change on water resources

by the 2080s are predicted to have increased by about 3 °C above today's (taken as the average over the period 1961–90). A global average temperature rise of 2 °C, which would occur by the 2050s with unmitigated emissions, will be delayed by about 50 years under 750 ppm stabilisation and by over 100 years under 550 ppm stabilisation. By the 2230s, global temperatures will have risen by just over 2 °C above today's under the 550 ppm stabilisation scenario, and just over 3 °C under the 750 ppm scenario.

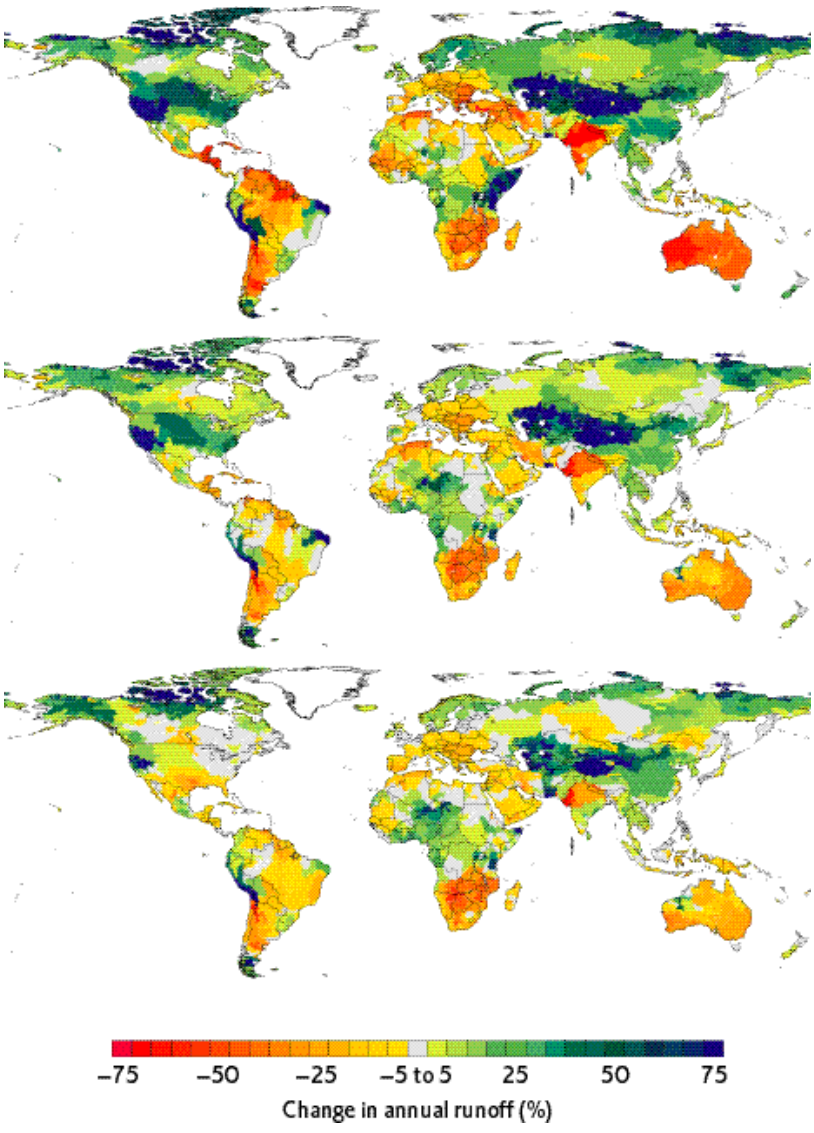
The pattern of temperature change by the 2080s (see page 6) is similar for all three emissions scenarios, but with a multiplying factor in line with global average temperature. The change in precipitation by the 2080s is shown on page 7 for the two stabilisation and unmitigated scenarios. Again the patterns are similar, but the magnitudes of change are smaller for the stabilisation scenarios, again, roughly in line with global temperature.

Beyond 2100, the temperature pattern under both scenarios which stabilise CO_2 concentrations shows a developing area of little temperature change in the Arctic Ocean north of Europe, and this feature is accentuated by the 2230s, as shown in the maps above. A plausible explanation is that it results from the accumulation of increased freshwater runoff into the Arctic Ocean acting to stabilise ocean convection, although this and other possible explanations are still under investigation.

Sea-level rise and ocean circulation

Sea level will rise from a combination of thermal expansion of ocean water, the melting of glaciers and changes to Greenland and Antarctic ice sheets. Changes under the unmitigated, 750 ppm and 550 ppm stabilisation scenarios are shown below, including all these contributions except Antarctica.

Over the next 100 years the contribution from melting of the Greenland ice sheet may be offset by increased precipitation over Antarctica, but by the end of the next century, temperatures may have risen sufficiently for melting of the Greenland ice sheet to double the rate of sea-level rise shown. In the longer term, continued warming may threaten the existence of the West Antarctic Ice Sheet, but the timing of this is very uncertain. The calculation of glacier melt becomes unreliable in the latter half of the scenarios, but by that time it is not a major component of sea-level rise. Because of the slow response of sea level to climate change, the delaying effect of the stabilisation scenarios is smaller than that in temperature



Percentage change in annual runoff by major river basin by the 2080s, relative to 1961–90, under the unmitigated emissions scenario (top) and emission scenario leading to stabilisation at 750 ppm CO_2 (middle) and 550 ppm CO_2 (bottom).

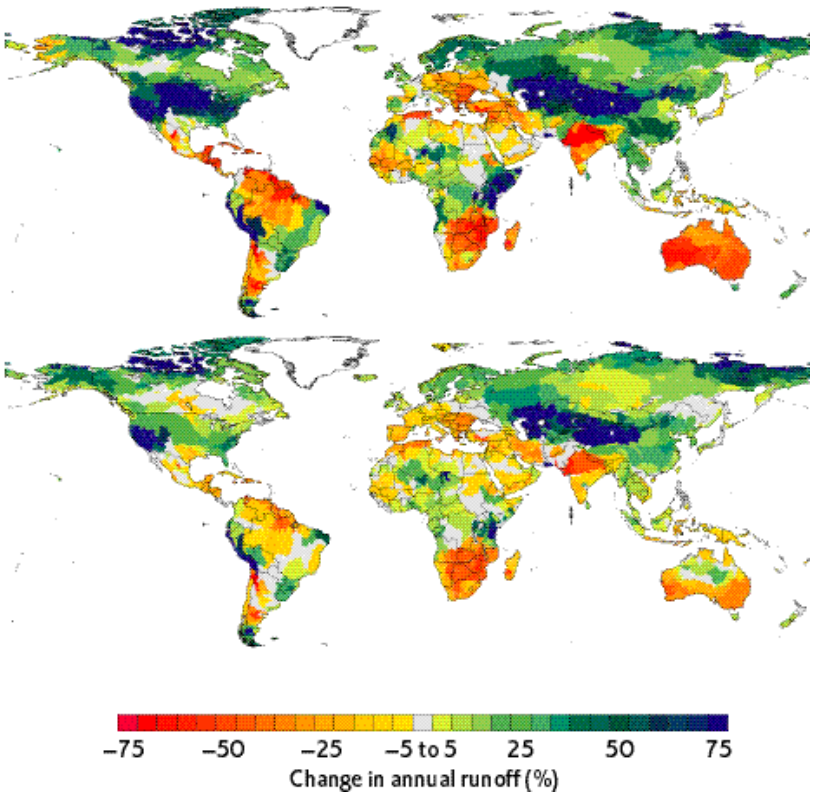
rise. The 22 cm sea-level rise (compared to 1961–90) expected by the 2050s with unmitigated emissions will occur approximately 15 years and 20 years later under the 750 ppm and 550 ppm stabilisation scenarios. The 50 cm sea-level rise expected by 2100 under unmitigated emissions will be delayed by about 35 years and 55 years respectively.

Unlike climate and impacts, which stabilise relatively soon after CO_2 in the atmosphere is stabilised, sea-level rise and its impacts will continue to increase for many centuries. To illustrate this, an idealised model experiment was run, where CO_2 concentration was increased by 1% per year for 70 years (until it had doubled) and was then held constant for 700 years afterwards. (Note that this scenario does not correspond to the three scenarios studied in the rest of this report.) The figure above right shows the total sea-level rise and two of its main components. Melting land ice (glaciers) will contribute to sea-level rise for about 400 years after CO_2 has been stabilised, until it has all melted. Thermal expansion of the ocean will continue for many hundreds of years after CO_2 is stabilised, due to the gradual penetration of heat deeper and deeper into the ocean. Thus, at any given time, in addition to the actual sea-level rise, there is a commitment to a substantial further sea-level rise which is unavoidable. This commitment is greatly increased once the warming becomes sufficient to threaten the existence of the Greenland and Antarctic ice sheets; their contributions are not shown because they are very uncertain.

In a previous report (November, 1998) it was shown that increasing greenhouse gases could cause a substantial reduction in the strength of ocean circulation in the North Atlantic, although not enough to prevent Europe from warming in line with the rest of the world. The changes in ocean circulation estimated from the unmitigated, 750 ppm and 550ppm stabilisation are shown below. Both the stabilisation scenarios lead to a recovery of ocean circulation to its original strength by 2200, at approximately the same rate.

Recent observations of climate change

As foreseen in the report issued in November 1998, the average global temperature in 1998 was higher than at any time since the mid-1800s, exceeding 1997 (the previous highest) by a substantial margin. Due in part to the ending of the 1997/98 El Niño, and reversal of sea-surface temperatures into a cool (La Niña) phase, 1999 has not been as warm as 1998. The global mean temperature up to the end of July 1999 is about 0.7 °C above that at the end of the last century (see diagram below); this may reduce a little further by the end of the year, but it is likely that 1999 will still be among the warmest ten years since global records began nearly 140 years ago. The



Percentage change in annual runoff by major river basins by the 2230s, relative to 1961–90, under emission scenarios which stabilise CO_2 concentration at 750 ppm (top) and 550 ppm (bottom).

decade of the 1990s is clearly the warmest on record, being about 0.6 °C warmer than that at the end of the last century.

In recent years there has been considerable debate about the extent to which temperature trends in the free atmosphere (i.e. well above the ground) deduced from satellite measurements show any warming. A high-quality record of temperatures in the lower part of the free atmosphere (at a height of 3–5 km) since the early 1960s has recently been generated at the Hadley Centre, using routine observations from weather balloons. If we compare the temperature changes at the surface with those in the free atmosphere (figure at top of next column), we see that there are periods of a decade or so where the atmospheric temperature rise drops below that at the surface, and the reason for this is still unclear. Nevertheless, the underlying warming trend is similar at the surface and in the atmosphere.

The Hadley Centre has also improved its record of Arctic sea-ice extent over the 20th century. The diagram below shows that the annual average area of sea ice has decreased in the last few decades. Each individual season also shows a downward trend, greatest in summertime. Although several large ice sheets have recently detached from the Antarctic peninsula, reliable records for the whole of Antarctica reach back only to 1975 and, despite an initial sharp drop, there has been no significant trend in sea-ice extent since then.

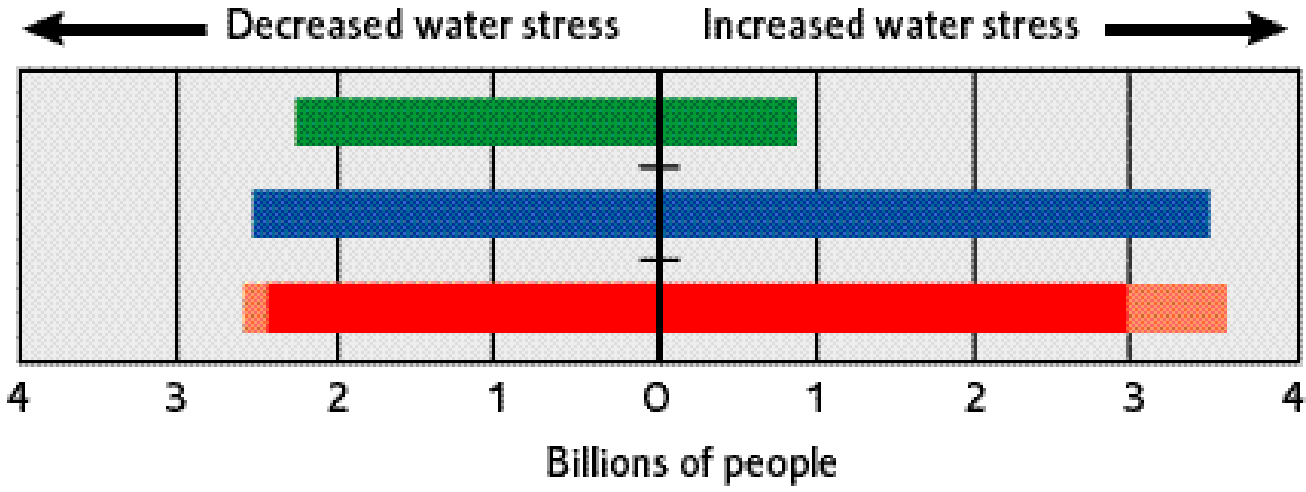
Contributors: Andrew White and Melvin Cannell, NERC Institute of Terrestrial Ecology, Edinburgh.

Summary

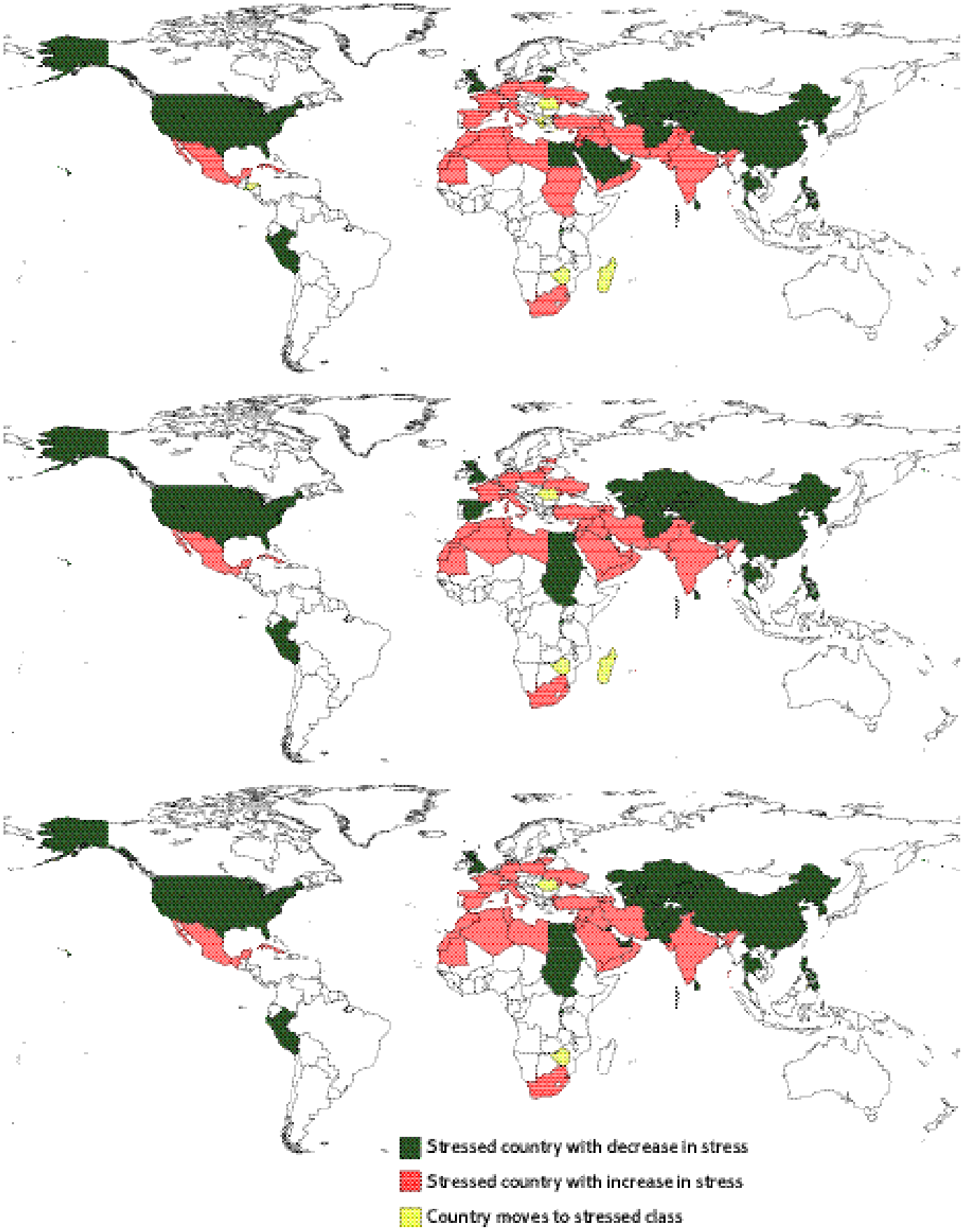
- With unmitigated emissions, substantial dieback of tropical forests and tropical grasslands is predicted to occur by the 2080s, especially in parts of northern South America and central southern Africa. Forests in North America, northern Asia and China are predicted to grow considerably.
- Under emissions scenarios leading to stabilisation of CO_2 at 750 ppm, the dieback of tropical forests is delayed by about 100 years, but under stabilisation at 550 ppm, this loss is substantially reduced, even by the 2230s.
- The absorption of carbon dioxide by vegetation increases during the 21st century in all scenarios. But, due to dieback in tropical vegetation, this sink is lost in the 2070s with unmitigated emissions and about 100 years later with emissions which stabilise CO_2 concentrations. Without this sink, CO_2 concentrations will be higher than assumed in the climate model, and hence climate change will be greater than current predictions.

Introduction

In Article 2 of the UN Framework Convention on Climate Change (UNFCCC), climate change is considered 'dangerous', and thus to be avoided, if it is likely to cause irreversible



Total number of people in the 2080s living in countries with water stress decreased (left) and increased (right) due to climate change under different emissions scenarios; unmitigated emissions (red/orange), emissions leading to 750 ppm (blue) and emissions leading to 550 ppm (green). For unmitigated emissions the red and orange bars represent the estimated range of values.



Change in water stress due to climate change by the 2080s, with unmitigated emissions (top) and under emission leading to stabilisation of CO_2 at 750 ppm (middle) and 550 ppm (bottom).

The impacts of climate change on food supply

damage to global ecosystems. In this report we assess the behaviour of global ecosystems using an ecosystem model (Hybrid) under climate change predictions derived from three different scenarios of CO_2 emissions. In particular we pay special attention to whether the terrestrial carbon sink, which currently sequesters around 25% of anthropogenic carbon emissions, can be sustained under the different scenarios of climate change and whether there are regions that are especially vulnerable to climate change. In this study, we take no account of the effect of changes in land use.

The Hybrid model simulates the global distribution of natural vegetation and carbon as it responds to changing climate, increasing atmospheric CO_2 and nitrogen deposition from the atmosphere. The model simulates the cycles of carbon, nitrogen and water between the soil and individual plants, with combinations of different plant types forming seven possible vegetation types — temperate grassland, tropical grassland, savannah, broadleaf evergreen forest, broadleaf cold deciduous forest, coniferous forest and mixed broadleaf/coniferous forest, plus desert (no vegetation). The type of vegetation that dominates in any region depends on the outcome of competition for light, nitrogen and water and the ability of plants to survive extreme conditions.

The distribution of vegetation and dieback

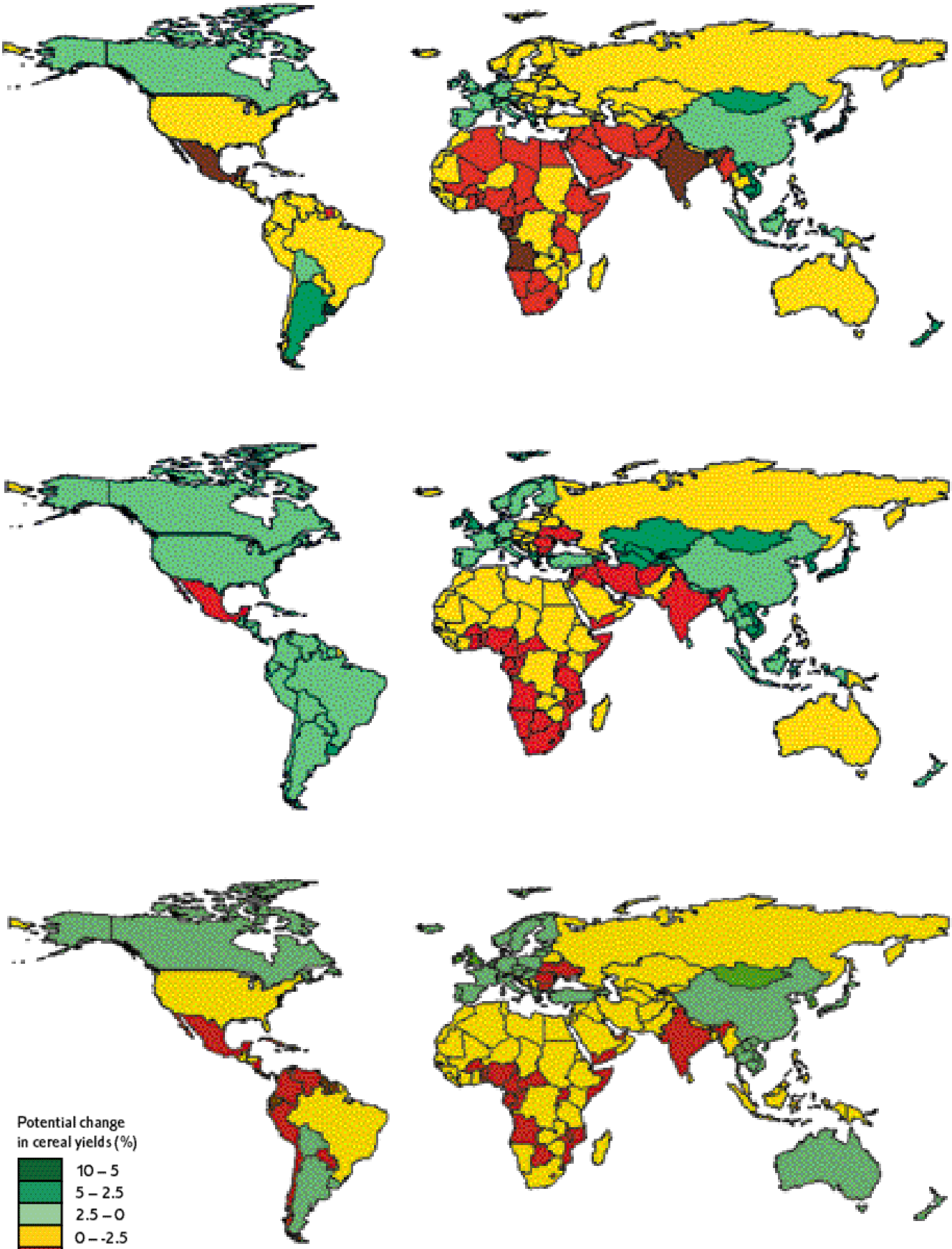
The maps overleaf show the distribution of vegetation biomass (kilogrammes of carbon per square metre) in the 1990s and the change in biomass between the 1990s and 2080s in response to climate change with unmitigated emissions, and emissions leading to stabilisation of CO_2 at 750 ppm and 550 ppm.

The maps above show the change in biomass which is predicted to occur by the 2230s under the stabilisation scenarios. The graph (top of next column) shows changes in the area of dieback — the area in which vegetation biomass has decreased below 10% of its present day value. Large decreases in biomass are predicted in tropical regions by the 2080s under the unmitigated emissions scenario and by the 2230s under emissions which stabilise CO_2 at 750 ppm. This decrease in biomass occurs because large areas of broadleaf evergreen forest (tropical rainforest) are predicted to be transformed to savannah, grassland and even desert, and also areas of tropical grassland are lost to desert. These losses are due to increases in temperature and decreases in rainfall. In the scenarios where emissions are unmitigated or lead to 750 ppm stabilisation, vegetation dieback is predicted to increase rapidly after 2050 with around three million square kilometres lost by 2100 and 2250, respectively. Under the emissions scenario leading to CO_2 stabilisation at 550 ppm, the decrease in vegetation carbon is reduced and the desertification of tropical forests does not occur. Thus, the area where vegetation dies back is reduced compared to the other scenarios, to around one million square kilometres by 2250, and can be attributed almost wholly to loss of tropical grasslands.

Under all the scenarios, there is an increase in vegetation biomass in regions north of 30° N. This is due to an increase in the biomass of existing forests in response to rising CO_2 and favourable climate change, which extends the growing season and provides more nutrients as a result of accelerated soil decomposition. Expansion in the area of broadleaf cold deciduous, coniferous and mixed forests does occur, but is less significant than growth within regions of established forest.

The global terrestrial carbon sink

The terrestrial sink has acted as a substantial 'brake' on the rate of increase of CO_2 in the atmosphere, and thereby slowed down global warming. The Hybrid model estimates this current terrestrial sink and how it may change under the three different scenarios of climate change. Under all climate change scenarios the overall trends in the uptake of carbon by vegetation are similar (see diagram below). In addition to long-term trends there is considerable decade-to-decade variability, due to natural variability in climate. There is an initial strengthening of the terrestrial carbon sink, up to the first quarter of the 21st century in the unmitigated emissions scenario, and up to the end of that century for the two stabilisation scenarios. In the unmitigated emissions scenario, this sink weakens and disappears by the 2070s. Under both the stabilisation scenarios, the loss of the vegetation carbon sink is delayed until about the 2170s; thereafter it is very variable but with a long-term sink close to zero. Thus, emissions which stabilise CO_2 concentrations delay the loss of the vegetation carbon sink by about 100 years but do not prevent the loss from occurring. Under the lowest emissions scenario, stabilisation of CO_2 is reached in 2150, and hence the loss of the sink in this scenario occurs as the biosphere relaxes to a new equilibrium. With unmitigated emissions, and the emissions which stabilise CO_2 at 750 ppm, the loss of sink occurs when the CO_2 concentration is still rising and is due to tropical vegetation dieback as warming and predicted shifts in rainfall reach critical levels.



Changes in crop yield by the 2080s, under scenarios of unmitigated emissions (top), and those which lead to stabilisation of CO_2 at 750 ppm (middle) and 550 ppm (bottom).

The impacts of sea-level rise

Contributor: Nigel Arnell, University of Southampton.

Summary

- With unmitigated emissions, by the 2080s, there are large changes predicted in the availability of water from rivers. Substantial decreases are seen in Australia, India, southern Africa, most of South America and Europe, and the Middle East. Increases are seen across North America, Asia (particularly central Asia) and central eastern Africa.
- An emissions scenario leading to stabilisation of CO_2 at 750 ppm generally slows down the rate of change in river flows, compared to an unmitigated emissions scenario, by about 100 years (more in Asia, slightly less in Europe). Stabilisation at 550 ppm delays the change still further, particularly in South America and Asia.
- With unmitigated emissions, water resource stress due to climate change by the 2080s is predicted to worsen in many countries (for example, northern Africa, the Middle East and the Indian subcontinent) but improve in others (for example China and the USA). Emissions leading to stabilisation at 550 ppm will reduce the number of people affected by water stress due to climate change from about three billion to about one billion. Stabilisation at 750 ppm has little effect on this total.

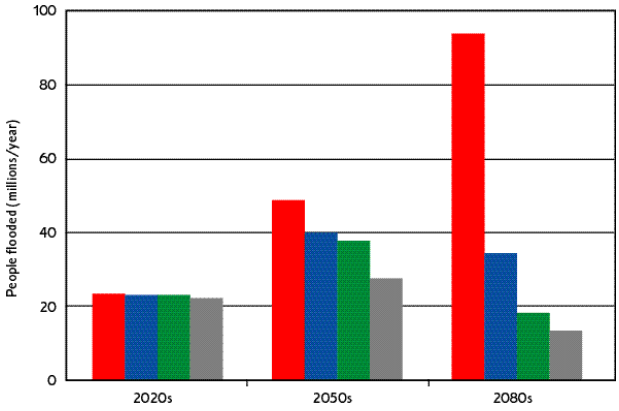
Introduction

At present, approximately 1.7 billion people, out of a population of around six billion, are living in countries experiencing water stress (defined as using more than 20% of their average annual renewable resources). The UN Comprehensive Assessment of the Freshwater Resources of the World estimates that by 2025, around five billion — out of a total population of eight billion — will be living in water-stressed countries. Climate change has the potential to alter these patterns of stress. Some parts of the world will receive more river runoff (but perhaps at the expense of increased flooding), while other parts will see a decrease in resource availability. The precise effect of climate change, however, depends on the relative rate of change in resource availability and demand increase; changes in the latter due to climate change are not considered. This section looks at how emissions scenarios leading to stabilisation of CO_2 at 750 ppm and 550 ppm affect water resource stress. First, it considers the effects of these scenarios on runoff and the resource base.

Changes in river runoff

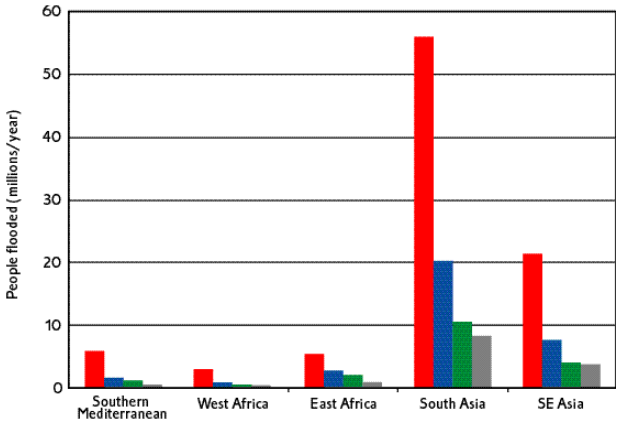
River runoff was simulated across the globe at a spatial resolution of 0.5° x 0.5° latitude and longitude, using a macroscale hydrological model run firstly with the observed 1961–90 global climate, followed by scenarios derived from the Hadley Centre predictions with an unmitigated emissions scenario and scenarios leading to CO_2 concentration being stabilised at 550 ppm and 750 ppm. Increasing CO_2 concentrations may affect evaporation rates directly by reducing stomatal conductance on the one hand but increasing plant leaf area on the other. The relative magnitudes of these two effects, however, are currently uncertain at the catchment scale, so have not been included in the current simulations. If CO_2 enrichment does reduce evaporation at the catchment scale, then the effects of stabilisation reported here may be overestimated.

The maps on the previous page show the percentage change in 30-year mean runoff by the 2080s, calculated across major river basins, under the unmitigated scenario and the two stabilisation scenarios. The broad spatial pattern of change is similar, but the magnitudes of change are smaller under the stabilisation scenarios. The two maps below show the percentage change in runoff by the 2230s under the two stabilisation scenarios. The changes under emissions leading to stabilisation at 550 ppm are broadly similar to those which would occur under the unmitigated emissions scenario around 180 years earlier (by the 2050s): the stabilisation at 750 ppm scenario produces greater change and therefore less of a delay.



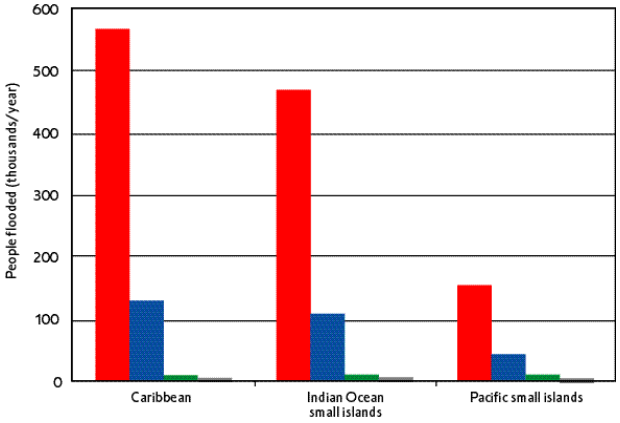
Average annual global number of people flooded for the 2020s, 2050s and 2080s under the three emissions scenarios: unmitigated (red), stabilisation at 750 ppm (blue) and at 550 ppm CO_2 (green). Also shown are the numbers without climate change (grey).

The effect of emissions leading to stabilisation on river runoff at continental scale has also been explored, although this can hide considerable within-continent variation. Stabilisation at 750 ppm tends to delay the change experienced under the unmitigated emissions scenario by the 2080s by around 100 years (slightly less in Europe, more in Asia). Stabilisation at 550 ppm delays the change still further, particularly in South America and Asia. However, there is considerable variability from one time period to another, reflecting climate variability. Up to the 2020s and, for some continents the 2050s, the change in runoff under the stabilisation scenarios is within the range of change estimated for the unmitigated emissions scenario. By the 2080s, both stabilisation scenarios generally result in change outside the range of uncertainty for the response from unmitigated emissions. In South America, the



Average annual number of people flooded for five vulnerable continental regions in the 2080s under the three emissions scenarios: unmitigated (red), stabilisation at 750 ppm (blue) and stabilisation at 550 ppm (green). Also shown is the case of no climate change (grey).

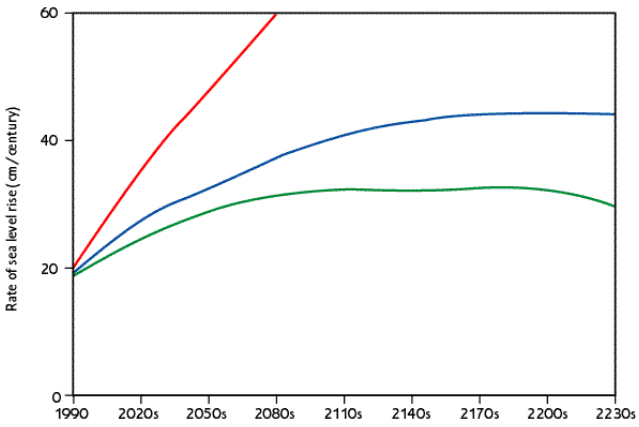
effect is very clear from the 2050s, while in Africa and Australasia, the effect is not significantly different from that due to unmitigated emissions through to the 23rd century.



Average annual number of people flooded for three island regions in the 2080s under unmitigated emissions (red), stabilisation at 750 ppm (blue) and stabilisation at 550 ppm (green). Also shown is the case with no climate change (grey).

Water resource stress

The indicator of water resource stress used here is the ratio of total national water withdrawals (as estimated for the UN Comprehensive Assessment of the Freshwater Resources of the World) to total national average annual runoff, including runoff imported from upstream countries. In the absence of climate change, by 2025, 2050 and 2085, approximately 5 billion, 6 billion and 6.5 billion people respectively will be living in countries using more than 20% of their resources, under the Comprehensive Assessment projections of population and water

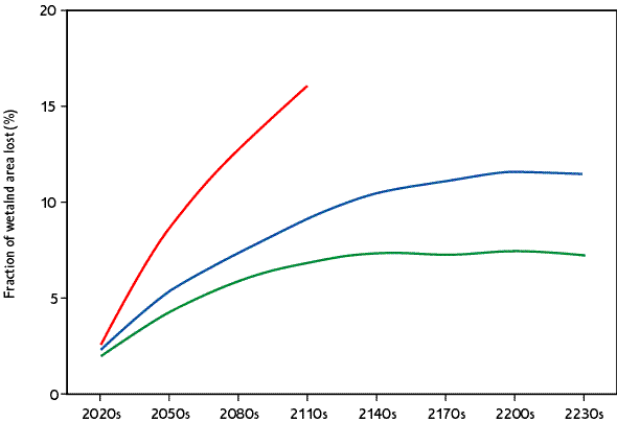


Rate of sea-level rise under unmitigated emissions (red), emissions leading to stabilisation at 750 ppm (blue) and stabilisation at 550 ppm (green).

use. As shown in the top map opposite, climate change will lead to a deterioration in resources in some of these countries (for example in northern Africa, the Middle East and the Indian subcontinent) and an improvement in others (for example, China and the USA). A small number of countries also move into the water-stressed category due to this climate change. The middle and bottom maps opposite show that emissions leading to stabilisation of CO_2 in the atmosphere may prevent some countries (such as Pakistan and Sudan)

from seeing an increase in stress.

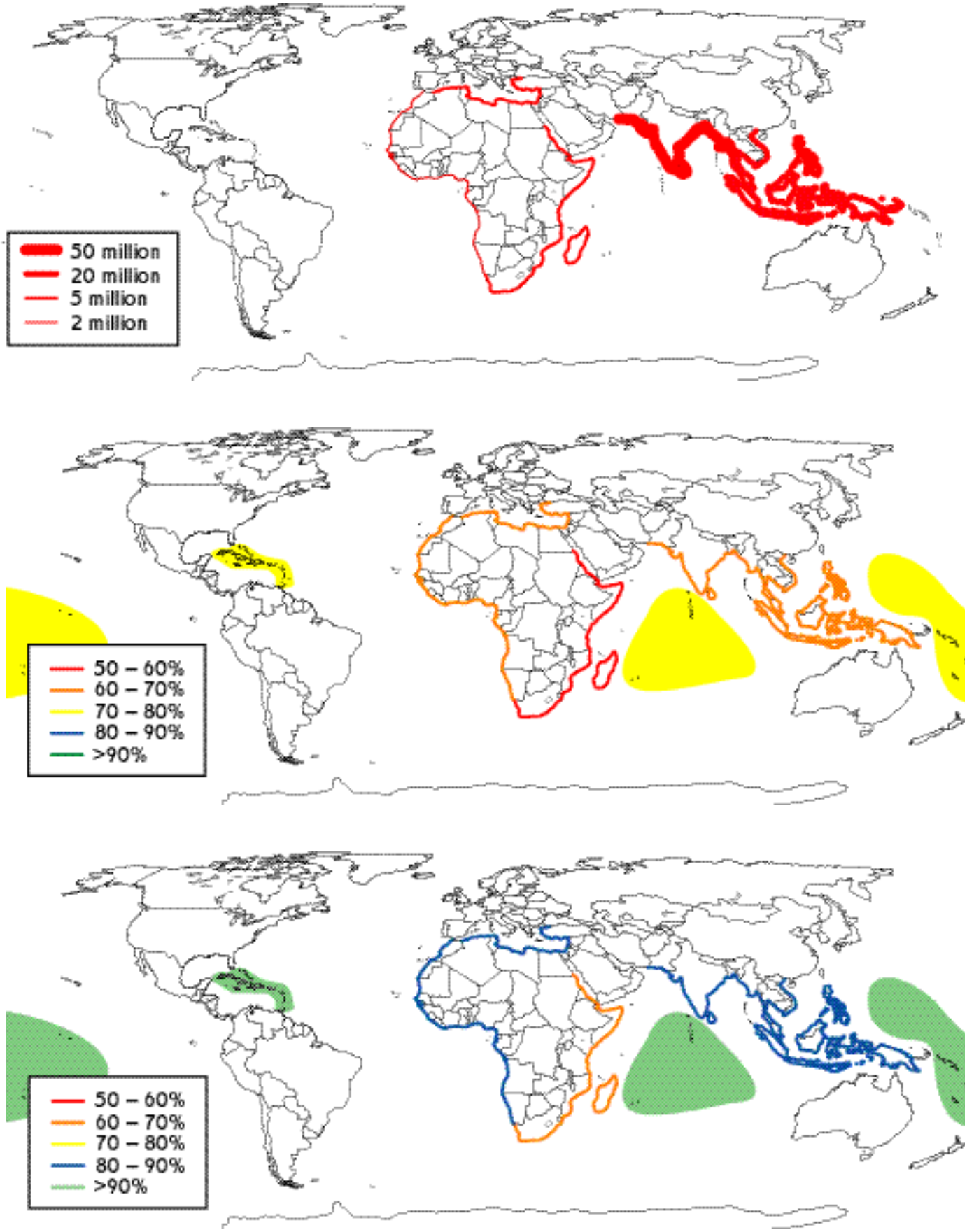
The total numbers of people living in countries with an increase in water stress (defined as seeing a reduction in resources of more than 10% or moving into the water stressed class), together with the total number living in countries with an decrease in water stress (an increase of resources of more than 10%) are calculated. By 2050, between 2.3 and 3.2 billion people would experience an increase in water stress under



Net global wetland losses relative to the 1990 stock under unmitigated emissions (red), emissions leading to stabilisation at 750 ppm (blue) and stabilisation at 550 ppm (green).

unmitigated emissions, but this would be reduced to 2.2 billion and 1.7 billion with 750 ppm and 550 ppm stabilisation scenarios, respectively. As shown in the diagram below, the effect of emissions leading to stabilisation at 550 ppm is considerably greater by the 2080s; the total population with increased water stress would fall from between 3 and 3.6 billion (with unmitigated emissions) to around 0.9 million, with relatively little change in the numbers of people with decreased water stress. Emissions leading to stabilisation at 750 ppm, have little effect on these numbers, however. Note that, in the above projections, no account is taken of the effect of climate change on demand for water.

There are regional differences in the effect of stabilisation. Impacts of climate change on water resource stress in Africa, for example, do not appear generally to be significantly reduced by stabilisation, although southern Africa does see some benefits. Some parts of the world — such as central America and much of Asia — show benefits of stabilisation at 750 ppm by the 2050s, while other regions do not. However, it is difficult to separate conclusively the effects of stabilisation from the effects of multidecadal variability, at least for the 750 ppm scenario.



The total annual number of people flooded in the 2080s, along the coastlines shown, under unmitigated emissions (top). The percentage reduction in numbers of people flooded (including in the island areas shown) under emissions leading to stabilisation of CO_2 at 750 ppm (middle) and 550 ppm (bottom).

The impacts of climate change on human health

Contributors: Martin Parry and Matthew Livermore, Jackson Environment Institute, University of East Anglia; Cynthia Rosenzweig, Goddard Institute for Space Studies, USA; Ana Iglesias, Universidad Politecnica de Madrid, Spain; Günther Fischer, International Institute for Applied Systems Analysis, Austria.

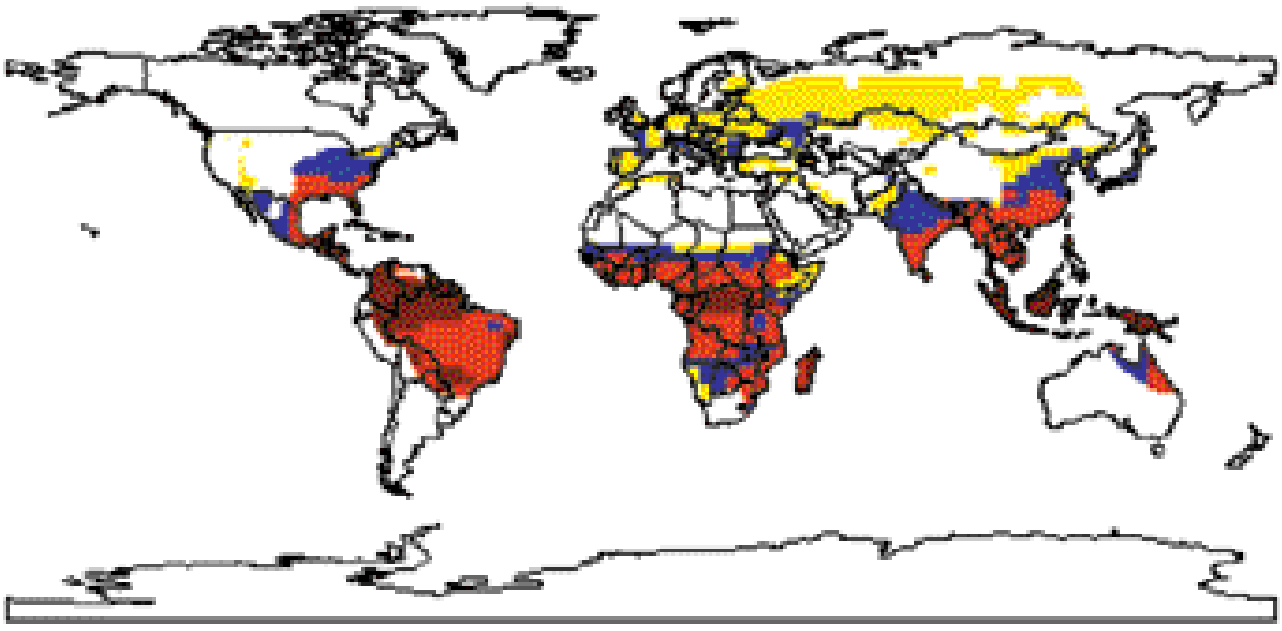
Summary

- By the 2080s, climate change and CO_2 increases due to unmitigated emissions are estimated to increase cereal yields at high and mid-latitudes, such as Canada, China, Argentina and much of Europe. At the same time, cereal yields in Africa, the Middle East and, particularly, India are expected to decrease.
- With emissions leading to CO_2 stabilisation, fewer regions experience negative impacts, although even under the 550 ppm scenario Africa and India are still adversely affected, and parts of South America are worse off than under unmitigated emissions. Under the 750 ppm stabilisation scenario, increasing CO_2 and climate change benefit production in areas of central Asia.
- The food system may be expected to accommodate such regional variations at the global level, with production, prices and the risk of hunger being relatively unaffected.
- However, some regions, particularly Africa, will be adversely affected, experiencing marked reductions in yield, decreases in production and increases in the risk of hunger.
- Reduction of emissions, leading to stabilisation of CO_2, appears to provide a way, in the short- to medium-term, of reducing the impacts of climate change on world food supply.

Crop yield changes

Validated dynamic crop growth models are used to simulate the effects of climate change and increased atmospheric CO_2 on the yield of major cereal crops. This is a preliminary assessment looking at the potential benefits of adopting emissions scenarios that lead to a stabilisation of CO_2 at 750 ppm and 550 ppm. Estimated changes in national grain crop yields were made based on simulations using IBSNAT/ICASA crop models and climate change scenarios at more than 120 sites. These models represent the important physiological processes responsible for plant growth and development and thus can estimate economic yield. They include major factors that affect yields, i.e. genetics, climate, soils, and management practices, and can be used to predict both rain-fed and irrigated crop yields.

The top map opposite shows shows the potential percentage changes in cereal yields in the 2080s with unmitigated emissions. This figure differs from that in the December 1997 report due to the use of updated crop models with smaller estimates of the potential benefits of CO_2 fertilisation and a slightly different climate change scenario. In comparison, the middle and bottom maps opposite show the potential changes in cereal yields under the emission scenarios leading



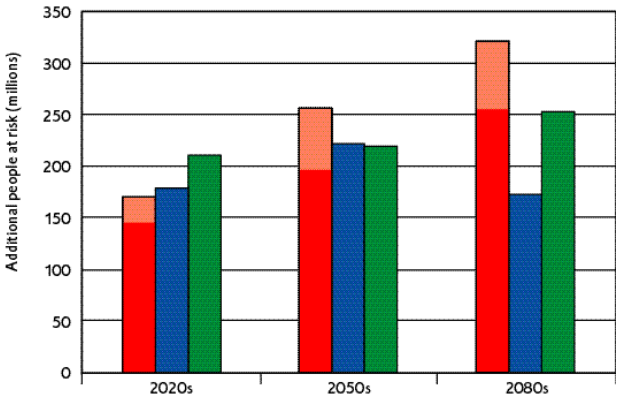
The length of transmission season for falciparum *malaria calculated for the present day.*

to stabilisation at 750 ppm and 550 ppm, again for the 2080s. The top map indicates that the pattern of yield changes under unmitigated emissions follows for the most part that of earlier studies reported in the IPCC Second Assessment Report, i.e., some small positive changes in the mid and high latitudes which are overshadowed by negative yield changes in the lower latitudes. Strong regional differences are seen in these results. For example, the Indian subcontinent and the Middle East suffer simulated yield losses while other regions (European Union, Japan, China and Canada) experience yield gains. Many of these potential benefits are very small and are not significantly different from those arising due to natural decade-to-decade variability.

In comparison the 750 ppm stabilisation scenario (middle map) indicates less reduction in yield in semi-arid subtropical regions such as northern Africa, Mexico and India. In addition mid-latitude regions (e.g. USA and central Asian countries such as Kazakhstan and Mongolia) exhibit potential increases in yield, particularly those which are predominantly producers of wheat — a crop which is known to benefit from higher photosynthetic rates and greater water use efficiency under elevated levels of atmospheric CO_2.

The pattern under the 550 ppm stabilisation scenario is less obvious: lower CO_2 levels and their associated climate changes suggest less reduction in yields than in the 750 ppm scenario in southern Africa, eastern Europe, the northern Middle East and Australia (bottom map). However, yield reductions appear to be greater in some areas (for example, the USA and Brazil) probably owing to the reduced fertilisation effect of lower CO_2 levels. In central and northern South America, these decreases are due to stress conditions imposed by temperature and higher evaporative demands on all crops for current agricultural systems of the region.

Note that this is a global and long-term assessment, focusing on average effects over space and time. At the local level (for example, in especially vulnerable areas) and over short periods (for example, in spells of drought or flooding) many of the effects of climate change on agriculture will be more adverse, as indicated in the IPCC Second Assessment Report.



The additional number of people at risk of falciparum *malaria in th 2080s, as a result of the unmitigated emissions scenario (the maximum and the minimum estates are shown in red and orange) and the emissions scenarios leading to stabilisation of CO_2 at 750 ppm (blue) and 550 ppm (green).*

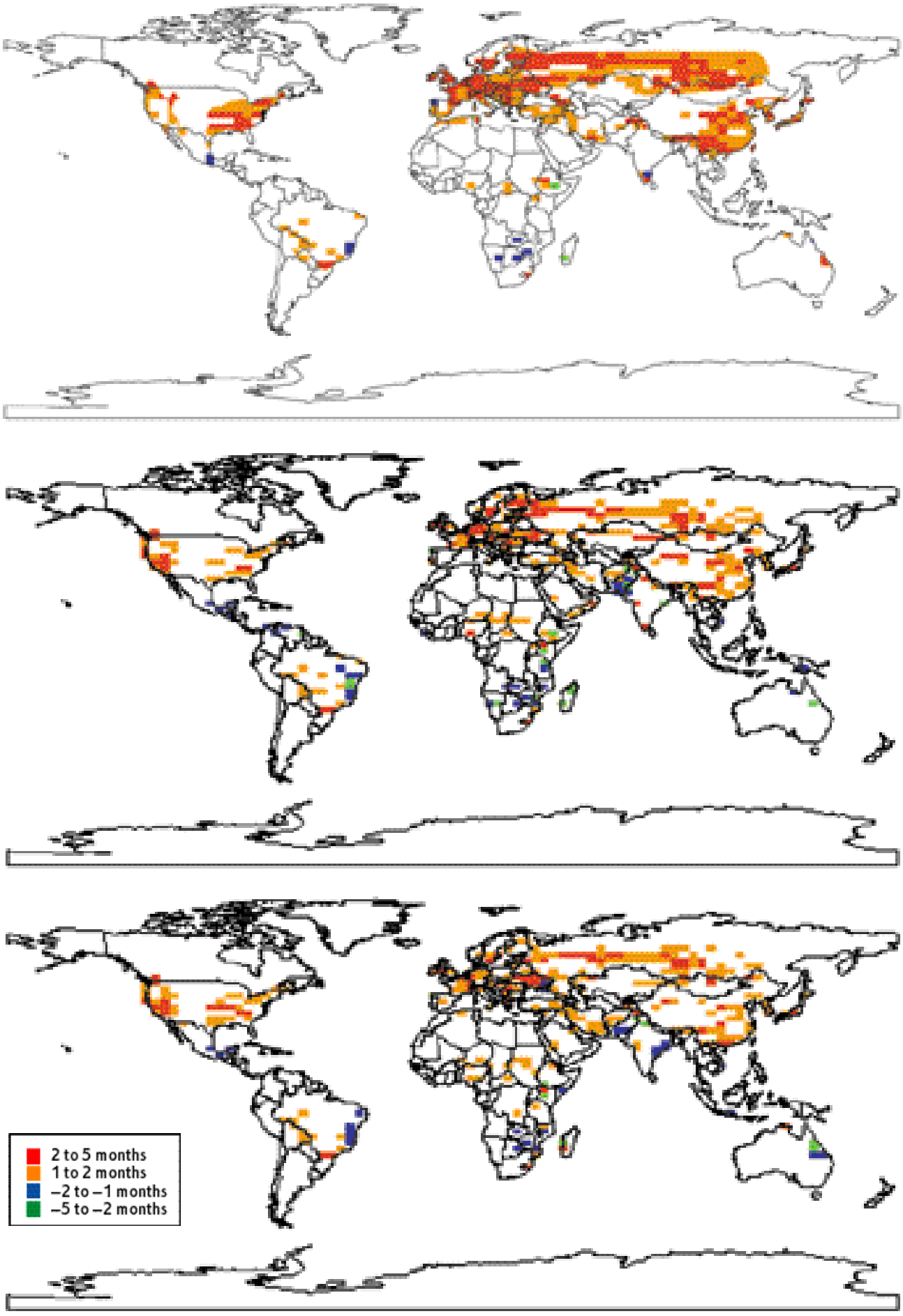
Contributor: Robert Nicholls, Middlesex University, London

Summary

- With unmitigated emissions, sea level will be about 40 cm higher than today by the 2080s, and this is estimated to increase the annual number of people flooded from 13 million to 94 million. 60% of this increase will occur in southern Asia (along coasts from Pakistan, through India, Sri Lanka and Bangladesh to Burma), and 20% will occur in South East Asia (from Thailand to Vietnam including Indonesia and the Philippines).
- The flood impacts of sea-level rise are reduced by the emissions scenarios leading to stabilisation of CO_2; by the 2080s, the annual number of people flooded is estimated to be 34 million under the 750 ppm scenario and 19 million under the 550 ppm scenario. Again, most of those flooded will be in southern and South East Asia.
- Under all emissions scenarios, sea-level rise will compound the existing decline of coastal wetlands due to direct human destruction. Under the stabilisation scenarios, wetlands will have longer to adjust and this will significantly reduce losses and aid their long-term survival.
- The continued rise in sea level even under the stabilisation scenarios would produce a range of progressive impacts on coastal lowlands and on low-lying coastal islands around the world without appropriate human adjustment and adaptation.

Introduction

Global warming causes sea level to rise by thermal expansion of the ocean waters and the melting of land-based ice, producing a range of impacts. In this study, we examine and compare the impacts of global mean sea-level rise due to unmitigated emissions, emissions leading to stabilisation at 750 ppm and 550 ppm CO_2. By the 2080s, the Hadley



The change in the duration of the transmission season for falciparum *malaria between the present day and the 2080s, under scenarios of unmitigated emissions (top), and emissions leading to CO_2 stabilisation at 750 ppm (middle) and 550 ppm (bottom).*

Centre predictions (illustrated in detail in the first section of this report) show a 41 cm global rise (compared to the level for 1961–90) in the case of unmitigated emissions, while the 750 ppm and 550 ppm stabilisation scenarios show rises of 30 cm and 27 cm, respectively. By the 2230s, even though CO_2 concentrations have stabilised, sea level will be higher by 94 cm and 75 cm, respectively, and still rising, due to its long adjustment time. This analysis considers, firstly, the increased risk of coastal flooding due to storm surges to the 2080s and, secondly, increased losses of coastal wetlands to the 2230s.

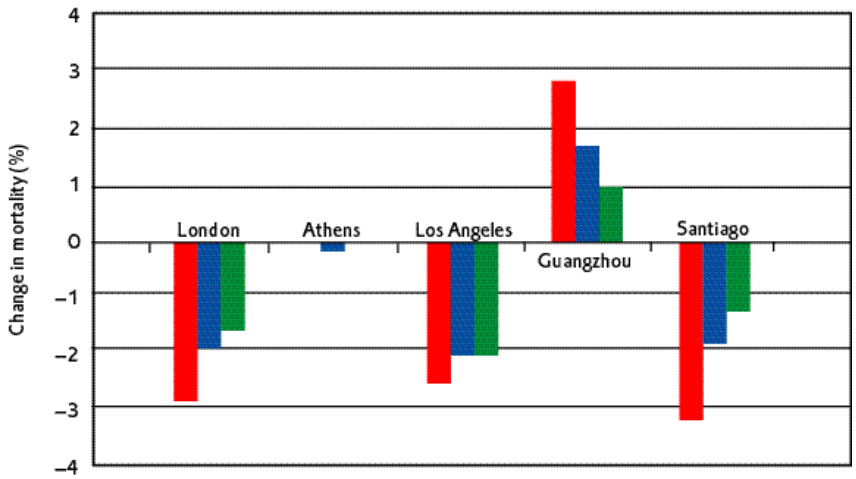
Coastal flooding

In assessing the risk of coastal flooding, the incidence of storms is assumed not to change, and the increase in frequency of high-water events arises only because of the rise in sea level. Population growth in the coastal zone is assumed to be double the national average, a projection of existing trends. The standard of flood protection is assumed to evolve from that of 1990 in line with the projected increase in GDP/capita, but with no measures introduced specifically to combat sea-level rise; historical precedent shows this to be a reasonable assumption. Calculations are made of the average number of people who are estimated to experience flooding per year by storm surges.

Globally, the average annual number of people flooded is calculated by the model to be 10 million in 1990; at the national level, these calculations agree well with available estimates. In the absence of any sea-level rise, this increases to 27 million in the 2050s, and then decreases to 13 million in the 2080s. Sea-level rise increases these numbers as shown in in the diagram below. Under the unmitigated emissions scenario, 94 million people will be flooded annually by the 2080s; an additional 81 million due to sea-level rise. The two stabilisation emissions scenarios result in smaller increases in numbers of people flooded, particularly after the 2050s. In the 2080s, 60 million fewer people are estimated to be flooded under stabilisation at 750 ppm, and 75 million fewer for stabilisation at 550 ppm.

The most vulnerable regions under the unmitigated emissions scenario are southern Asia (along coasts from Pakistan, through India, Sri Lanka and Bangladesh to Burma), South East Asia (Thailand to Vietnam, including Indonesia and the Philippines), with lesser but still substantial numbers in eastern Africa (South Africa to Sudan, including Madagascar), the Mediterranean from Turkey to Algeria and western Africa (Morocco to Namibia). By the 2080s, under the unmitigated emissions scenario more than 90% of the average annual number of people flooded would be found in these five regions with southern Asia contributing the great majority. The diagram below and the maps overleaf show the extent to which the numbers of people who experience flooding are significantly reduced in all these regions under the stabilisation scenarios, compared to unmitigated emissions.

In relative terms, the island states in the Caribbean, the Indian Ocean (excluding Sri Lanka and Madagascar) and the Pacific Ocean appear particularly vulnerable to unmitigated emissions. The diagram at the top of the next column shows clearly how



Change in mortality rate due to urban stress as a result of unmitigated emissions (red), and emissions scenarios leading to stabilisation of CO_2 at 750 ppm (blue) and 550 ppm (green).

the numbers of people who experience flooding are significantly reduced in all these regions under the scenarios leading to stabilisation of CO_2.

Impacts on coastal wetlands

Direct human reclamation is reducing the global stock of coastal wetlands (i.e. saltmarshes, mangroves and intertidal areas) by about 1% per year. Even if this rate of decline were to be moderated substantially, wetlands could still be reduced by about 40% by the 2080s. Added to this reduction will be a further loss due to sea-level rise from human-induced global warming. Coastal wetlands are sensitive to sea-level rise as their location is intimately linked to present sea level. For wetland loss, the rate of sea-level rise is more important than the absolute rise as wetlands have some capacity to respond to sea-level rise by vertical accretion due to sediment and organic matter input. As shown in the graph below, under the unmitigated emissions scenario, the rate of global sea-level rise increases with time approaching 60 cm/century by the 2080s. Under the stabilisation emissions scenarios the rate of global sea-level rise increases much more slowly and levels off at just over 40 cm/century for the stabilisation at 750 ppm scenario and about 30 cm/century for the stabilisation at 550 ppm scenario, beginning to decrease in the 23rd century.

The direct wetland response to sea-level rise is modelled by selecting a critical rate of long-term sea-level rise as a proportion of local tidal range above which wetland losses commence. Wetland losses are assumed to occur 30 years after any sea-level rise, reflecting response lags. The potential for wetland migration on to adjacent low-lying upland is evaluated, based on coastal morphology and the occurrence or absence of coastal protection (estimated from the predicted coastal population density in the 2080s). This latter factor restricts the potential for wetland migration compared to earlier periods of climate change and sea-level rise in the earth's history. While there are significant uncertainties in the calculation a best estimate of wetland losses (shown in the graph below) illustrates the relative impacts for the different emissions scenarios. Note that these losses are in addition to the direct effect of wetland reclamation mentioned earlier.

Under unmitigated emissions, losses increase rapidly with time and, by the 2080s, 13% of the 1990 global wetland stock would be destroyed by sea-level rise. Substantial additional losses would be expected in the 22nd century. The stabilisation scenarios show a large reduction in the losses in the 2080s to 7% (CO_2 stabilisation at 750 ppm) and 6% (CO_2 stabilisation at 550 ppm). After the rate of sea-level rise levels off, no further wetlands are lost. This happens by the 2200s for the stabilisation at 750 ppm scenario when losses reach 12%, and in the 2140s for the stabilisation at 550 ppm scenario when losses reach 7%. These losses are less than those under the unmitigated scenario in the 2080s. After the rate of sea level-rise has stabilised, a slow recovery of the wetlands might begin. Therefore, stabilisation of CO_2 concentrations could make an important contribution towards the long-term survival of coastal wetlands. The coastal wetlands of the Mediterranean, the Baltic and the Atlantic coast of North and Central America appear particularly vulnerable to sea-level rise, and will suffer substantial losses by the 2080s under all climate change scenarios.

An important aspect of rising sea level is its long timescale. As seen in the first section of this report, even if climate change is halted, the warming already incurred will progressively penetrate deeper and deeper causing sea level to continue to rise for many centuries. This will threaten coastal lowlands and low-lying islands with a range of impacts including erosion, inundation, increased flooding and salinisation. Some human adjustment and adaptation to sea-level rise would appear to be essential even under stabilisation scenarios.